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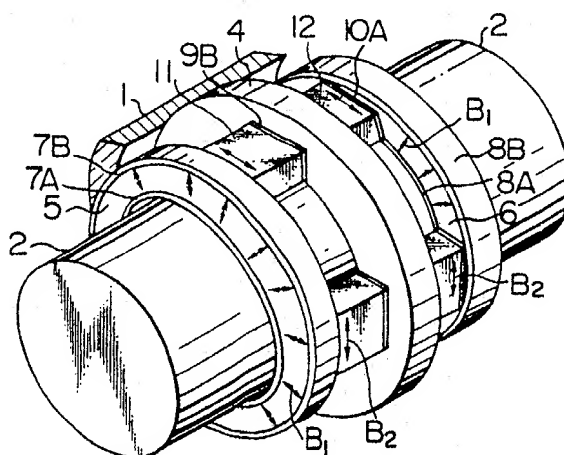
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⑤④ **Rotary actuator.**

⑤⑦ A rotary actuator for converting electrical energy into rotating torque comprises a stator (1), a rotor (2), a pair of annular first piezoelectric elements (5, 6) contracting and expanding in the radial direction in response to the application of an electrical signal, and a plurality of second piezoelectric elements (11, 12) disposed between the first piezoelectric elements (5, 6) and a holding portion (4) of the stator (1) for causing displacement of the first piezoelectric elements in the circumferential direction in response to the application of the electrical signal. These piezoelectric elements (5, 6, 11, 12) are alternately energized to continuously rotate the rotor (2).



ROTARY ACTUATOR

1 This invention relates to a rotary
actuator for converting electrical energy into
rotating torque, and more particularly to a rotary
actuator using a piezoelectric element for the
5 electro-mechanical conversion.

 A rotary actuator used for actuating,
for example, each of articulations of a multi-
articulate robot is required to be small in size,
light in weight and yet to be capable of generating
10 a large actuating force. Rotary actuators of
this kind employed hitherto include a rotary
actuator of electric type such as an induction
motor, a synchronous motor or a DC motor and a rotary
actuator of hydraulic type such as an oil hydraulic
15 motor. In order that a rotary actuator of
electric type as described above can generate a
large torque at a low rotation speed, a reduction
gearing having a very large reduction ratio is
required. Therefore, the structure of a drive
20 system therefor becomes quite complex, resulting in
an increased weight and a reduced mechanical
efficiency. Further, such a rotary actuator
requires brake means for stopping the rotation of
and maintaining the position of the rotary actuator.
25 On the other hand, the use of a rotary actuator of

1 hydraulic type as described above is accompanied
by the problem of maintenance such as leakage of
oil.

Piezoelectric elements have been widely
5 utilized in various fields in recent years, and
many rotary actuators using piezoelectric elements
have been proposed hitherto. An example of such
a rotary actuator is disclosed in United States
Patent No. 4,019,073.

10 The rotary actuator of the kind using
a piezoelectric element is required to be capable
of generating a large torque at a low rotation
speed and to be small in size, light in weight and
simple in structure.

15 It is therefore an object of the present
invention to provide a rotary actuator of the
kind using a piezoelectric element for the
electro-mechanical conversion, which is capable of
continuously supplying a rotating torque.

20 Another object of the present invention
is to provide a rotary actuator of the kind above
described, which is small in size and light in
weight.

Still another object of the present
25 invention is to provide a compact rotary actuator
of the kind above described.

In accordance with the present invention
which attains the above objects, there is provided

1 a rotary actuator for converting electrical
energy into rotating torque comprising a stator,
a rotor supported by the stator so as to be
rotatable relative to the stator, a holding member
5 provided on the stator so as to extend toward
the rotor, annular first drive means disposed on
both sides of the holding member for clamping and
releasing the rotor by making expansive and
contractive deformations in the radial direction
10 thereof, second drive means disposed between and
fixed to the first drive means and the holding
member for causing rotary movement of the first
drive means around the rotor, and means for
applying an energizing voltage to the first and
15 second drive means.

Other objects, features and advantages
of the present invention will be apparent from
the following detailed description of preferred
embodiments thereof taken in conjunction with
20 the accompanying drawings, in which:

Fig. 1 is a schematic longitudinal
sectional view of a preferred embodiment of the
rotary actuator according to the present inven-
tion;

25 Fig. 2 is a partly sectional, schematic
perspective view of the rotary actuator of the
present invention shown in Fig. 1;

Fig. 3 is a circuit diagram of a circuit

1 driving the rotary actuator of the present invention shown in Fig. 1;

Fig. 4 is a time chart showing one form of the signal pattern supplied from the
5 signal generator in the drive circuit shown in Fig. 3;

Fig. 5 is a time chart showing one form of the operation cycle of the rotary actuator of the present invention shown in Fig. 1;

10 Fig. 6 is a partly sectional, schematic perspective view of another embodiment of the rotary actuator according to the present invention; and

Fig. 7 is a partly sectional, schematic
15 perspective view of still another embodiment of the rotary actuator according to the present invention.

A preferred embodiment of the rotary actuator according to the present invention will now be described in detail with reference to
20 Figs. 1 to 3. Referring to Figs. 1 and 2, the reference numeral 1 designates a cylindrical body functioning as a stator. A shaft 2 is shown in bearings 3 to be rotatably supported in this cylindrical body 1. This shaft 2 functions as
25 a rotor. A holding member 4 extends from the inner peripheral surface of the cylindrical body 1 toward the shaft 2. A pair of annular first piezoelectric elements 5 and 6 are disposed on

1 both sides respectively of the holding member 4.
These first piezoelectric elements 5 and 6 are
provided at their inner and outer peripheries
with a pair of electrodes 7A, 7B and a pair of
5 electrodes 8A, 8B respectively. The first piezo-
electric elements 5 and 6 are so polarized that
the direction of polarization A_1 coincides with
their radial direction. Such a manner of polariza-
tion can be attained by applying a high voltage
10 across the piezoelectric elements 5 and 6 thereby
making uniform the direction of polarization in
the piezoelectric elements. When an electric
field of the same direction as the polarized
direction A_1 is applied by the electrode pairs 7A,
15 7B and 8A, 8B to the first piezoelectric elements
5 and 6 polarized in the manner above described,
a longitudinal strain of the same direction as
the polarized direction A_1 and a lateral strain
orthogonal to the longitudinal strain occur in
20 the first piezoelectric elements 5 and 6. In this
case, the lateral strain is dominant over the
longitudinal strain to cause an expansive strain
and a contractive strain in the radial direction B_1
as shown in Fig. 2. When the contractive strain
25 occurs in the first piezoelectric elements 5 and 6,
the first piezoelectric elements 5 and 6 are
brought into engagement at their inner periphery
with the shaft 2 to clamp the shaft 2. On the other

1 hand, when the contractive strain appears then
in the first piezoelectric elements 5 and 6, the
shaft 2 is released from the state clamped by
the first piezoelectric elements 5 and 6. Fig. 1
5 illustrates that the first piezoelectric element 6
clamps the associated portion of the shaft 2
since the contractive strain occurs therein,
while the other first piezoelectric element 5
releases the associated portion of the shaft 2
10 from the clamped state since the expansive strain
occurs therein, thereby forming a very small gap
between its inner periphery and that portion of
the shaft 2.

A plurality of second piezoelectric
15 elements 11 and 12 are disposed between and fixed
to the first piezoelectric elements 5, 6 and the
holding member 4 through a pair of electrodes 9A,
9B and a pair of electrodes 10A, 10B respectively
around the shaft 2. These second piezoelectric
20 elements 11 and 12 are polarized in a direction A_2
tangential to the shaft 2 as shown in Fig. 1.
Therefore, when an electric field is applied by
the electrode pairs 9A, 9B and 10A, 10B to the
second piezoelectric elements 11 and 12 in a
25 direction orthogonal to the polarized direction A_2 ,
a so-called shearing strain whose direction
coincides with the polarized direction A_2 , that is,
the direction shown by the arrow B_2 in Fig. 2

1 occurs in the portions of the second piezoelectric
elements 11 and 12 adjacent to the first piezo-
electric elements 5 and 6. When such a shearing
strain appears in the second piezoelectric elements
5 11 and 12, the first piezoelectric elements 5 and
6 are displaced in the circumferential direction
by an amount corresponding to the amount of the
shearing strain.

The fundamental structure of a preferred
10 drive circuit supplying an energizing voltage to
the first piezoelectric elements 5, 6 and second
piezoelectric elements 11, 12 will be described
with reference to Fig. 3. This drive circuit
includes a switching circuit 301 connected to the
15 piezoelectric elements 5, 6, 11, 12 and a signal
generator 302 controlling the switching circuit 301.
Terminals 303 of the switching circuit 301 are
connected to a voltage source (not shown). The
switching circuit 301 includes a plurality of
20 switching sections connected at their output
terminals to the piezoelectric elements 5, 6, 11
and 12 respectively, and each of these switching
sections includes a pair of transistors T_1 , T_2 ,
a resistor R and an inverter INV. At the input
25 terminals, these switching sections are connected to
channels CH_1 to CH_4 of the signal generator 302
respectively. Fig. 4 shows one form of the signal
pattern applied from the channels CH_1 to CH_4 of

1 the signal generator 302. In Fig. 4, this signal
pattern is illustrated to have a rectangular
waveform.

When now a high level of the rectangular
5 waveform signal is applied from the channel CH_1
of the signal generator 302 to energize the first
piezoelectric element 5, the associated transistors
 T_1 and T_2 in the switching circuit 301 are turned
on and off respectively, and the voltage applied
10 from the voltage source to the associated terminal
303 is charged to the piezoelectric element 5
through the associated resistor R. On the other
hand, when a low level of the rectangular waveform
signal is then applied from the channel CH_1 of the
15 signal generator 302, the associated transistors T_1
and T_2 in the switching circuit 301 are now
turned off and on respectively, thereby discharging
the voltage applied to the piezoelectric element 5.

Description will now be directed to
20 how the embodiment of the rotary actuator of
the present invention shown in Fig. 1 is operated
according to the signal pattern shown in Fig. 4.
Fig. 5 is a time chart showing how the piezoelectric
elements 5, 6, 11 and 12 operate with time T in
25 response to the signal pattern shown in Fig. 4.
Fig. 5 shows in A the time chart of operation of
the piezoelectric element 5 and in B that of the
piezoelectric element 6. In each of the curves in

1 A and B, a positive portion indicates that an
expansive strain occurs to release the shaft 2
from the clamped state, while a negative portion
indicates that a contractive strain occurs to
5 clamp the shaft 2. Fig. 5 shows in C the operating
state of the piezoelectric elements 11, and in D
that of the piezoelectric elements 12. In each
of the curves in C and D, a positive portion indicates
that the piezoelectric elements 11 and 12 are
10 deformed to cause counter-clockwise rotation of
the piezoelectric elements 5 and 6 respectively,
while a negative portion indicates that the piezo-
electric elements 11 and 12 are deformed to cause
clockwise rotation of the piezoelectric elements 5
15 and 6 respectively. Fig. 5 shows in E the angular
displacement of the shaft 2 relative to the
cylindrical body 1. In Fig. 5, all of the horizontal
axes represent the time T, and (1) to (6) represent
the sequential steps of operation.
20 In the step (1) in Fig. 5, the piezo-
electric element 6 expands to clamp the shaft 2,
while the piezoelectric element 5 contracts to
release the shaft 2 from the clamped state.
In the step (2), the piezoelectric
25 elements 12 are deformed to cause counter-clockwise
rotation of the piezoelectric element 6 by one
step, while, at the same time, the piezoelectric
elements 11 are deformed to cause clockwise rotation

1 of the piezoelectric element 5 by one step.

Consequently, the shaft 2 is rotated counter-clockwise by one step relative to the cylindrical body 1.

5 In the step 3 , the piezoelectric element 5 contracts to clamp the shaft 2.

In the step (4) , the piezoelectric element 6 expands to release the shaft 2 from the clamped state.

10 In the step (5) , the piezoelectric elements 11 are deformed to cause counter-clockwise rotation of the piezoelectric element 5 by one step, while, at the same time, the piezoelectric elements 12 are deformed to cause clockwise rotation
15 of the piezoelectric element 6 by one step.

Consequently, the shaft 2 is rotated counter-clockwise by one step relative to the cylindrical body 1.

In the step (6) , the piezoelectric element
20 6 contracts to clamp the shaft 2. This clamping exhibits a brake action holding the shaft 2 in its clamped state after the energizing voltage ceases to be applied.

By execution of the above six steps
25 constituting one cycle, the shaft 2 is rotated counter-clockwise by two steps relative to the cylindrical body 1.

By repetition of the above operation

1 thereafter, the shaft 2 can be rotated counter-
clockwise continuously.

Although the above description has
referred to the operation mode for rotating the
5 shaft 2 counter-clockwise in Fig. 2, it is readily
apparent that the voltage may be applied to cause
reverse operation of the piezoelectric elements 11
and 12 in the operation time chart of Fig. 5 for
causing clockwise rotation of the shaft 2 in Fig. 2.

10 Fig. 6 shows another embodiment of
the rotary actuator according to the present
invention, and the same reference numerals are
used in Fig. 6 to designate the same parts appearing
in Fig. 1. In this second embodiment, the second
15 piezoelectric elements 11 and 12 of shearing strain
type are replaced by piezoelectric elements 13
of bimorph type. As in the case of the piezo-
electric elements 11 and 12 of shearing strain
type shown in Fig. 1, a plurality of such piezo-
20 electric elements 13 of bimorph type are disposed
between the holding member 4 and the first piezo-
electric elements 5, 6 so as to cause displacement
of the piezoelectric elements 5, 6 in the circum-
ferential direction. According to this second
25 embodiment, the amount of circumferential displace-
ment of the piezoelectric elements 5 and 6 can
be increased although the force generated by
the piezoelectric elements 13 of bimorph type

1 is small compared with the piezoelectric elements 11 and 12 of shearing strain type. Therefore, an actuator can be provided in which the rotor can be rotated at a higher speed.

5 Fig. 7 shows still another embodiment of the rotary actuator according to the present invention, and the same reference numerals are used in Fig. 7 to designate the same parts appearing in Fig. 1. The third embodiment is constructed
10 so that the shaft 2 functions as the stator, and the cylindrical body 1 is rotatable relative to the shaft 2 to function as the rotor. To this end, the shaft 2 is provided with a holding member 14 for holding the second piezoelectric elements 11
15 and 12 coupled to the first piezoelectric elements 5 and 6 respectively. This holding member 14 extends from the shaft 2 toward the cylindrical body 1. The outer peripheral surface of the first piezoelectric elements 5 and 6 acts as a
20 working surface engaged with and disengaged from the inner peripheral surface of the cylindrical body 1 to clamp and release the cylindrical body 1 when the first piezoelectric elements 5 and 6 are subjected to contraction and expansion. The
25 operation of this third embodiment is similar to that of the embodiment shown in Fig. 1, and, therefore, any detailed description thereof is unnecessary. Since a piezoelectric body has generally

1 a very strong resistance to a compressive stress
than a tensile stress, the arrangement of the
embodiment of Fig. 7 in which the first piezo-
electric elements 5 and 6 are pressed against the
5 inner periphery of the cylindrical body 1 for
clamping is effective for improving the useful
service life of the first piezoelectric elements 5
and 6.

In the embodiment shown in Fig. 7 too,
10 the second piezoelectric elements 11 and 12 may be
replaced by the bimorph elements shown in Fig. 6.
Further, the second piezoelectric elements 11 and
12 may be of a single layer structure or of a
laminated structure having many electrodes. Further,
15 although the second drive means are coupled to
the side faces of the first drive means in the
aforementioned embodiments, the present invention
is in no way limited to such a coupling mode,
and the second drive means may be coupled to the
20 inner or outer periphery of the first drive means.
Further, the signal supplied from the signal
generator in the drive circuit is in no way limited
to the rectangular waveform signal described above,
and an analog signal such as a sinusoidal waveform
25 signal may be supplied. Further, a plurality of
rotary actuators as described above can be
disposed in a relation juxtaposed in the axial
direction.

- 1 It will be understood from the foregoing detailed description that the present invention provides a rotary actuator which can continuously supply rotating torque and which is small in size,
- 5 light in weight and compact in structure.

CLAIMS:

1. A rotary actuator for converting electrical energy into rotating torque comprising:

a stator (1);

5 a rotor (2) supported by said stator so as to be rotatable relative to said stator;

a holding member (4) provided on said stator so as to extend toward said rotor;

10 annular first drive means (5, 6) disposed on both sides of said holding member for clamping and releasing said rotor by making expansive and contractive deformations in the radial direction thereof;

15 second drive means (11, 12) disposed between and fixed to said first drive means and said holding member for causing rotary movement of said first drive means around said rotor; and

means (301) for applying an energizing voltage to said first and second drive means.

20 2. A rotary actuator as claimed in Claim 1, wherein said stator is a cylindrical body (1), said rotor is a shaft (2) inserted into said cylindrical body to be rotatably supported by said cylindrical body, and said holding member (4) extends from
25 said cylindrical body toward said shaft for holding said second drive means (11, 12) coupled to said first drive means (5, 6).

3. A rotary actuator as claimed in Claim 2,

wherein said first drive means includes annular piezoelectric elements (5, 6) and a pair of electrodes (7A, 7B; 8A, 8B) provided on the inner and outer peripheries of each of said piezoelectric elements.

4. A rotary actuator as claimed in Claim 3, wherein said second drive means includes piezoelectric elements (11, 12) of shearing strain type and a pair of electrodes (9A, 9B; 10A, 10B) provided on each of said piezoelectric elements to extend in a direction parallel to the direction of polarization of said piezoelectric element.

5. A rotary actuator as claimed in Claim 3, wherein said second drive means includes piezoelectric elements (13) of bimorph type making a deflective deformation in response to a voltage applied thereto.

6. A rotary actuator as claimed in Claim 4, wherein at least one of said annular piezoelectric elements (5, 6) constituting said first drive means acts to still clamp said rotor (2) due to a contractive strain persisting after it is deenergized.

7. A rotary actuator as claimed in Claim 5, wherein at least one of said annular piezoelectric elements (5, 6) constituting said first drive means acts to still clamp said rotor (2) due to a contractive strain persisting after it is deenergized.

8. A rotary actuator as claimed in Claim 1,

wherein said stator is a shaft (2), said rotor is a cylindrical body (1) surrounding said shaft to be rotatably supported by said shaft, and said holding member (14) extends from said shaft toward the inner periphery of said cylindrical body for holding said second drive means (11, 12) coupled to said first drive means (5, 6).

9. A rotary actuator as claimed in Claim 8, wherein said first drive means includes annular piezoelectric elements (5, 6) and a pair of electrodes (7A, 7B; 8A, 8B) provided on the inner and outer peripheries of each of said piezoelectric elements.

10. A rotary actuator as claimed in Claim 9, wherein said second drive means includes piezoelectric elements (11, 12) of shearing strain type and a pair of electrodes (9A, 9B; 10A, 10B) provided on each of said piezoelectric elements to extend in a direction parallel to the direction of polarization of said piezoelectric element.

11. A rotary actuator as claimed in Claim 9, wherein said second drive means includes piezoelectric elements (13) of bimorph type making a deflective deformation in response to a voltage applied thereto.

12. A rotary actuator as claimed in Claim 10, wherein at least one of said annular piezoelectric elements (5, 6) constituting said first drive means

acts to still clamp said rotor (1) due to a tensile strain persisting after it is deenergized.

13. A rotary actuator as claimed in Claim 11,
wherein at least one of said annular piezoelectric
5 elements (5, 6) constituting said first drive
means acts to still clamp said rotor (1) due to
a tensile strain persisting after it is deenergized.

FIG. 1

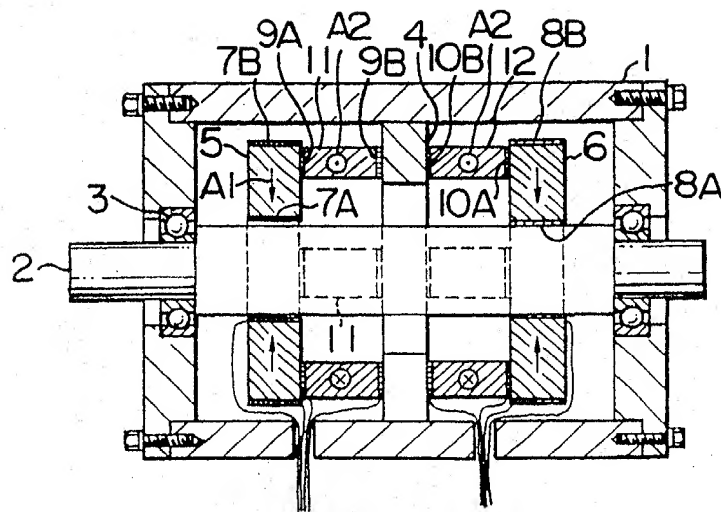


FIG. 2

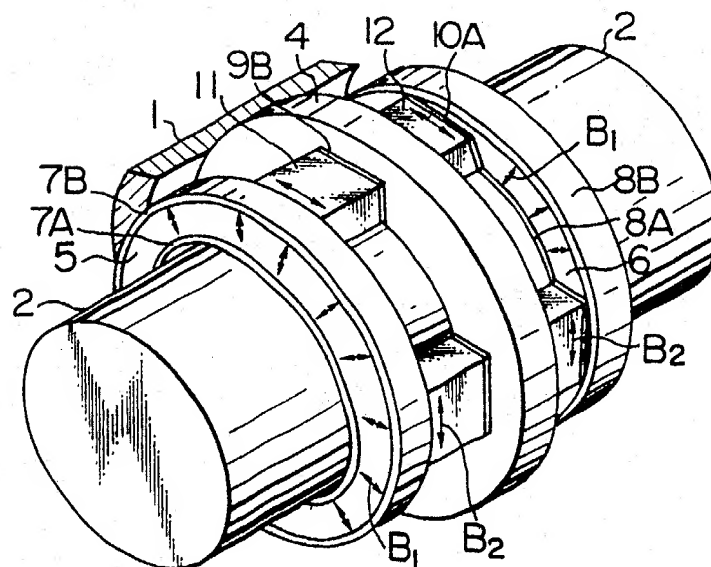


FIG. 3

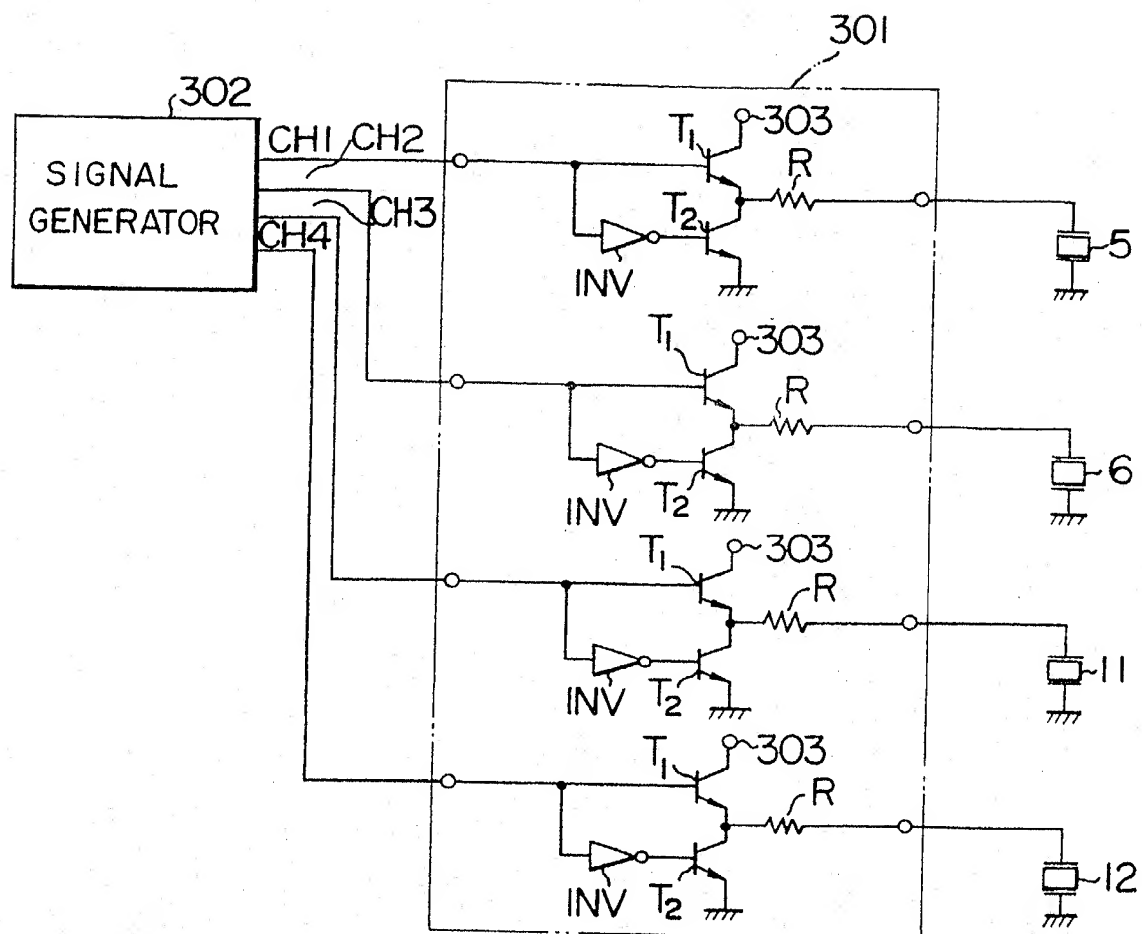


FIG. 4

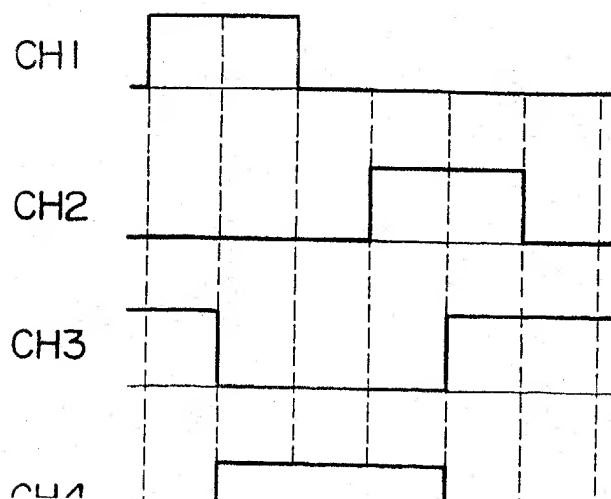


FIG. 5

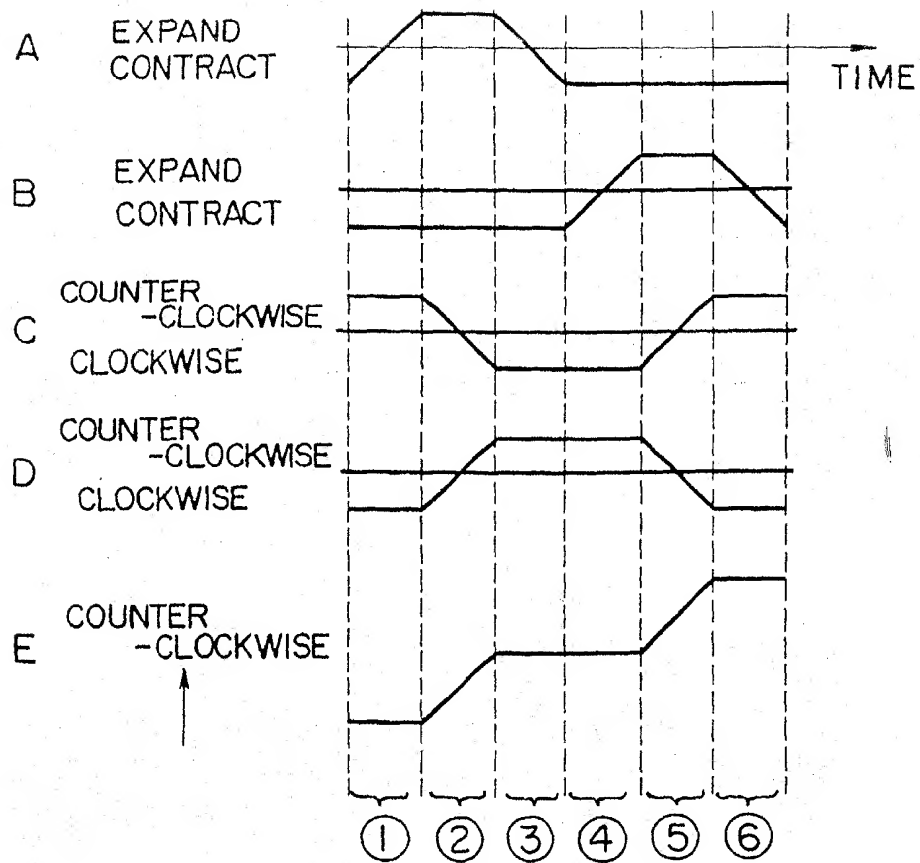


FIG. 6

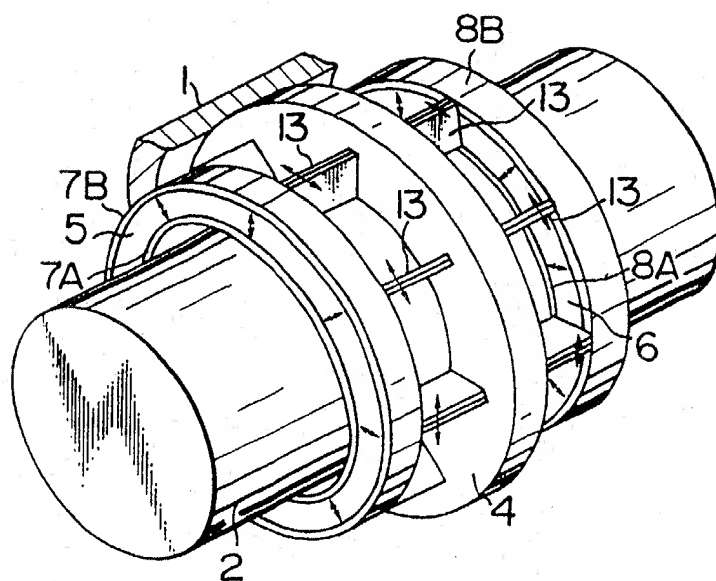


FIG. 7

